8 Prospects for Biological Carbon Sinks in Greenhouse Gas Emissions Trading Systems

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8.1 Introduction

The role of sinks in climate policy has been controversial and confused. The major supporters for including sinks in an international climate policy under the Kyoto Protocol were the Umbrella Group of countries, led by the USA and including Australia, Canada, Japan and Russia. This group also pushed strongly for international emissions trading, imagining that countries would distribute emissions allowances to private sector emitters, who would then be required to have an allowance for each tonne of greenhouse gas (GHG) they emitted. With emissions trading, emitters who found they could cheaply reduce their emissions might have allowances to sell, or those who could not easily reduce these could purchase allowances to cover their emissions. With international trading, these permits could be exchanged among allowance holders anywhere among the parties subject to an emissions cap.

In principle, accounting and crediting sinks under a cap-and-trade system should be straightforward: (i) measure the stock of carbon at an initial year; (ii) measure the stock of carbon in subsequent years; (iii) if the carbon stock rises from one period to the next, the increased sequestration is added to the allowances or cap on emissions of the country or entity, and if the stock declines, the net release to the atmosphere is subtracted from the allowances or cap. This simplicity has eluded designers of carbon policy. For various reasons, a desire has developed to identify specific types of sink-enhancement actions that may or may not be included under agreed caps as well as an unwillingness to bring the entire terrestrial biosphere carbon stock within a policy target. The result has been thousands of pages of attempts to define a forest, the difference between afforestation and reforestation, what constitutes 'management', if a change in carbon stocks is due to human action, and spatial and temporal leakage. Most of this would be irrelevant if a simple accounting framework and broad coverage of land use emissions and uptake were adopted in the design of carbon policy. How and why did we get from a simple and straightforward idea to the complex design and controversial issues now discussed as part of sinks policy? Are there good reasons why the problem is not as simple as it at first seems? Is it possible (or desirable) to now try to work towards fairly simple mechanisms for sinks in a carbon policy? These are the questions we hope to address in this chapter.

We first review existing policies with attention to issues that arise with regard to

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terrestrial sinks, and how sinks are to be included. We then show some of the important aspects of managing sinks that arise because they depend on environmental conditions that are largely outside the control of the land owner. Next we work through a very simple example of two hypothetical countries, and show the effects of including sinks. Finally we address several issues that have arisen as countries have negotiated the inclusion of sinks in GHG mitigation policies. Some of these are important and real issues that must be addressed if climate policy design is to create incentives for efficiently managing carbon in the terrestrial biosphere. However, many of the issues arise from, or in response to, the tangled policy approaches we have designed for sinks enhancement, and attempts to straighten it out seem only to further tangle the issue.

8.2 Current Climate Policies, Emissions Trading and the Role of Sinks

After fighting hard for sinks and emissions trading in the Kyoto Protocol, the USA and Australia are among the few countries that, while having signed the Protocol initially, have now expressed their intention of not ratifying it. Thus, key Conference of the Party (COP) members who had pushed hardest for inclusion of sinks are now not part of the Protocol. Canada has ratified and is perhaps most active among ratifying parties in developing measuring and monitoring techniques that they hope would allow expanded inclusion of sinks. After much uncertainty, the Protocol entered into force because Russia ratified the agreement. With Russia, emissions of ratifying Annex B members – who took on binding caps under the Protocol – exceed 55% of the 1990 emissions of the original Annex B list. This was the key threshold for entry into force as set out in the Protocol, and Russia's ratification brought the parties across that threshold (UNFCCC, 1997, 2005).

Australia has indicated that, while not ratifying Kyoto, it would meet its obligations under the agreement. What this means is unclear, but it may affect the sinks issue. If not formally under Kyoto, Australia could pursue a strategy of meeting the numerical target while defining credits for land-use change beyond the limits of the Protocol. The possibility of crediting reduced rates of deforestation against Australia's target was identified in at least one study of the pros and cons of Australian ratification (Kyoto Ratification Advisory Group, 2003). At this point, the chance that the USA would meet the numerical target set out under Kyoto seems remote. The Bush administration announced instead an emissions-intensity target that would allow emissions to rise somewhat from 2000 levels, which contrasts with the Kyoto requirement that the USA return to 93% of 1990 levels (White House, 2002). For the time being the administration believes its intensity target will be met through voluntary measures. The administration pressured industries to identify emissions-reducing actions, and attempted to publicize these promises. Given the nature of the target and the promised actions, varying changes in emissions intensity in different industries, and changing industry composition over time, it is hard to determine with any rigour whether the actions proposed are sufficient to meet the intensity goal. The other continuing effort in the USA is a programme whereby entities can receive recognition for reducing emissions or enhancing sinks by being awarded 'registered reductions' (Federal Register, 2002). The 'incentive' to do so is either goodwill or, more likely, expectations that at some point, there will be a mandatory cap on at least some entities and that registered reductions could be applied to them.

Despite the absence from the Protocol of the USA and Australia, the key supporters of trading, the push for emissions trading appears to have taken hold to some extent under Kyoto. The EU has developed an emissions trading system, and introduced a test phase (2005–2007) that will run prior to the first commitment period of the Kyoto Protocol (EC, 2003, 2005; Betz *et al.*, 2004). So even though the EU was initially hesitant on emissions trading, it now appears to be a major force in designing a domestic system that could be a model for other parties, making the vision of an international market for permits a reality (Ellerman, 2001). There is, however, still a long way to go to extend such a trading system among all ratifying parties. The EU's test programme is limited to large emitting point sources (>10,000 t CO_2/year) and thus covers less than half of the EU's total CO_2 emissions. Other key parties including Canada, Japan and Russia have not yet moved to establish emissions trading systems. Performance in the EU's trading system from 2005 to early 2006 resulted in prices on the order of ~20–28/t CO_2, surprisingly high to many analysts because the required reduction was estimated to be only ~1% (Pew Center, 2005; Point Carbon, 2005a,b). In May 2006, the price dropped to as low as ~9/t CO_2 and trading was generally in the range of ~10–20/t CO_2.

While emissions' trading remains alive under the Protocol, the Umbrella group's push for sinks was not nearly as successful. Part of the reason why agreement was not reached at the 6th meeting of the COP in The Hague in November 2001 was that the EU held out for limits on the total quantities of sinks credits that could be applied against each country's emissions cap, and this was unacceptable to the USA. Even before George W. Bush was elected President and announced the USA's rejection of the Protocol, the failure at The Hague was essentially the death knell of Kyoto in the USA (Reiner, 2001; Reilly, 2003). The difference in willingness to embrace sinks appears to derive from different views of the nature of the climate change issue as a societal problem. Many in Europe saw the response to the climate change problem as part of an even broader agenda of switching from fossil fuels to 'renewable' sources of energy. The use of sinks was, in the view of some at least, denial or avoidance of these necessary steps to turn the economy away from fossil fuels. In the language of economics, this view might be cast as one in which markets had failed to price fossil fuels to include all of the social costs associated with them (everything from security, air pollution, other health and safety issues, their nature as exhaustible resource, etc.). Rather than try to correct each of these problems, renewable energy proponents see the answer as simply switching away from fossil fuels. Sinks credits were thus seen as a loophole, allowing continued fossil fuel use. This view has appeared to influence the EU's climate change – negotiating positions and the formulation of its domestic policies.

In contrast, the perspective of the USA and Umbrella group concentrated directly on the climate GHG problem, and for carbon this meant focusing on actions that would limit atmospheric concentrations of CO_2. It mattered little whether fossil fuel emissions were reduced or carbon uptake by vegetation and soils was increased, or carbon was otherwise sequestered. One tonne removed from the atmosphere was just as good as reducing emissions by a tonne. This focus, along with a desire for cost-effectiveness, led to a desire for maximum flexibility in choosing the least costly way to reduce atmospheric CO_2 levels. Separate quantity limits on the use of sinks, if binding, would result in a two-tier permit market – a higher price for emissions reduction and lower price for sinks, reflecting the fact that there were more cheap sinks options available than allowed by the restriction on their use. Most analysts believe that the sinks quantities allowed in the Kyoto Protocol as finally negotiated at COP 7 in Marrakesh in 2001 are so limiting, and the definition of what can be counted so loose that the agreement has been widely modelled as simply a relaxation of the constraint on emissions (Babiker *et al.*, 2002). Underlying this view is the calculation that most countries are likely to have enough carbon uptake in forests without doing anything more than they would have done anyway to fill their sinks limit. In particular, the Protocol allows consideration of forest uptake anytime from 1990 through 2012 to be credited against emissions in the first commitment period of 2008–2012.

The language of the agreement requires some sort of active management to get credit for carbon uptake. For some countries, the implicit definition of 'management' was very narrow: identified tracts of land that were replanted, or planted, and managed with the express intent of storing carbon. Analysts began referring to 'Kyoto forests' to represent the idea that lands earning credits for forest activities would be specifically identified. However, the USA, leading up to the COP meeting at The Hague in 2000, proposed that 'forest management is an activity involving the regeneration, tending, protection, harvest, access and utilization of forest resources to meet goals defined by the forest landowner' (UNFCCC, 2000).

This broad definition would bring in essentially all forestland, at least in the USA and the most developed countries, if not in most of the world, if only because property laws that limit access would, under this definition, seem to qualify the land as 'managed'. Taking this interpretation would essentially mean that all carbon accumulated by forest regrowth during the 2008–2012 period would be creditable against a country's Kyoto target, up to the limits set at Marrakesh.

While the logical basis for including sinks in climate policy is strong, the weak link in the argument is the lack of proven methods for measuring and monitoring them. At the time (and still today) a complete inventory of carbon sinks for all the major parties is not available, and there are legitimate questions about the accuracy of even the best of these inventories. Negotiating the Kyoto Protocol caps with sinks broadly included would have meant that the negotiating countries did not know their own 1990 net emissions baselines, nor did they have much idea of what they would be in 2010. With a cap on fossil emissions there was some certainty, or so it seemed, that the parties to the agreement would lower emissions by about 5% below the 1990 level. Because the forest area of the capped parties together formed a substantial net sink, if all of that could have been credited against emissions, the end result would be that emissions would be higher in 2008–2012 than in 1990 rather than lower. Lacking resolution on how to interpret key terms in the Protocol, the quantified limits on sinks finally agreed upon gave up some of the 5% reduction that would have been achieved, but with the exact sink quantities specified it was not an open-ended amount.

The specific numerical limits on which Europe insisted at The Hague, and those finally reached at Marrakesh, ended a very confusing and complex discussion of just how to include sinks. With these numerical limits the other language that would limit sinks is far less important if not irrelevant. The 'success' of the negotiated limits is that countries can stretch the bounds of plausibility of sinks accounting, if they so desire, but clever interpretation and accounting can never get more credits than the numerically limited amount. The 'failure' is that if it is possible to easily fill up the sinks limit with sinks that would have occurred anyway, the strict limits remove any incentive to actually enhance biological sinks. That is, in a cap-and-trade system, no matter what the allowance price, the credit price for sinks credits would be limited and could approach zero because the use of credits was limited far below the amount that could be forthcoming. For example, the Energy Information Administration (EIA, 2003) analysis of a cap-and-trade system in the USA, with a limit on credits, projected a two-tier pricing result with a lower price for credits than for allowances.

The combination of several factors – (i) the withdrawal of the USA and Australia where emissions are growing rapidly; (ii) a target for Russia and the transition economies of Eastern Europe well above expected emissions (so-called hot air); and (iii) the sinks quantities that were ultimately allowed – has led many analysts to conclude that the cap on the remaining parties may be nonbinding in the first commitment period anyway (e.g. Bohringer, 2001; Manne and Richels, 2001; Babiker *et al.*, 2002). So even without generous sinks accounting, it is far from certain that the emissions target in Kyoto will lead to real environmental gains. If it does, it will be the result of countries doing more than they pledged under the agreement (by implementing domestic policies and not fully availing themselves of the excess credits above reference emissions from Russia – so-called hot air). Sinks credits can also be brought into play under the clean development mechanism (CDM) and a number of proposed projects are now undergoing the review process.

As noted above, the current stated policy of the USA is to reduce GHG intensity by 18% over the decade. Most analysis shows that emissions intensity has historically improved at 14%, and so achieving 18% would be a modest reduction below the reference growth. Others dispute this, forecasting that an 18% improvement would occur if nothing were done (e.g. Reilly, 2002). Given the uncertainty, this is probably well within projection error, even if one accepts 14% improvement as the median estimate.

Other unilateral policies have been proposed in the USA, most notably the Climate Stewardship Act of 2003 (S. 139), widely known as the McCain–Lieberman Bill after the senators who co-sponsored the legislation. As introduced legislation, it produced some specific details of what a mitigation programme would look like if this Bill had become law. It was a cap-and-trade with year 2000 emissions as the benchmark, and fairly broadly covered emissions of GHGs. The cap did not cover land use sources or sinks or small sources (<10,000 t CO_2 equivalent), although it did cover transport fuel by bringing it under control at the refinery. Small sources and terrestrial sinks of any size were covered under a crediting system, but the total number was limited to a percentage of the total allowances. Paltsev *et al.* (2003) and EIA (2003) analysed at some length the economic implications of the Bill, and discussed its provisions. While numerically different from the Kyoto target for the USA, the mechanism for sinks – project credits produced outside the cap with a limit on how many could be applied under the cap – is essentially the mechanism of the Kyoto Protocol. Not straying too far from the existing international agreement is perhaps good news if one has hopes that the USA would at some point join it, but bad news if one is looking for innovative policy design that leads to effective and efficient management of carbon in the biosphere. The Bill failed to pass in the Senate, but once-drafted Bills are often reintroduced or the language in them borrowed for succeeding attempts to draft a Bill. Thus, even in failure it provides some guide as to how the US Congress might approach the problem of mitigating climate change.

Having described the complexity of sinks inclusion in the Kyoto Protocol, a final requirement here is to review the language of the Protocol that includes sinks. The complexity derives (apparently) from a compromise among those wanting to limit sinks and those wanting broad coverage. Thus, we end up with an attempt to limit sinks offsets by defining specific sinks projects on which all could agree. These are 'Article 3.3 sinks' as the language is laid out there. It allows 'removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation, and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period' to be used to meet commitments under the Article.

Defining reforestation versus afforestation has required people to imagine how far back in history or prehistory one might go to determine whether a forest was there or not. Defining a forest has required consideration of the minimum density and height of the woody vegetation (Birdsey *et al.*, 2000). The debate has a tendency to become philosophical as analysts grapple with attributing some part of sink increase to 'direct human-induced' change apart from that due to natural causes or indirect actions by humans.

Those pushing for broader inclusion of sinks hold out hope for the so-called 'Article 3.4 sinks'. The language here opens up consideration at the first meeting of the parties (MOP), to occur upon entry into force of the Protocol, or as soon as practicable thereafter of the 'modalities, rules and guidelines as to how, and which, additional human-induced activities related to changes in greenhouse gas emissions by source and removals by sinks in the agricultural soils and the land-use change and forestry categories shall be added to, or subtracted from, the assigned amounts for Parties'.

Apparently, as it became clear that the language of Article 3.3 could be interpreted to render the limits not very binding, the absolute numerical limits on sinks were brought to the table, and then limits were ultimately agreed on. If, in fact, the original motivation for the narrow definition of Article 3.3 was concerned that excessive sinks would be credited, the eventual agreement to strict numerical limits would seem to make the entire distinction among these different categories irrelevant, yet the language persists. We turn now to biophysical aspects of the sinks issue that relate to the policy discussion above, and to our practical suggestions for how sinks might be included in a cap-and-trade system in later sections.

8.3 Important Biophysical Aspects of Sinks that Shape Their Inclusion in Trading

Forest and soil sinks depend jointly on natural processes and the actions of humans. A farmer or forester manages the land; that management affects the rate of vegetation growth (carbon uptake) and decomposition (return of carbon to the atmosphere). Carbon storage occurs if for some reason the uptake exceeds decomposition, and for the storage to be meaningful, average uptake must exceed decomposition for some number of years, otherwise one is simply tracking diurnal and seasonal cycles. The joint dependence on actions by humans and on the response of natural systems raises some issues in considering biological carbon management. We will argue later that these differences do not pose major problems for inclusion of sinks in a cap-and-trade system providing reasonable procedures can be established for measuring carbon storage and tracking changes in it. It should be noted that energy systems also have a joint dependence on nature and human management. Energy demand for space conditioning is weather- and climate-dependent, as severe weather can damage or interfere with energy infrastructure, and renewable energy such as hydro, solar, wind and biomass is at least as dependent on nature as is carbon storage in biological systems. A severe drought might disrupt vegetation growth or lead to a forest fire and thus to unplanned carbon emissions. That same drought might lead to low hydro capacity, increase demand for electricity for air conditioning and be associated with a lack of wind to power wind turbines. An electricity generator might then need to rely on existing fossil-generating capacity more than expected, leading to unplanned emissions of CO_2. The unique features of the interaction between nature and management are important considerations in the design of a carbon trading system, and how it will work, but they are not a barrier to establishing markets for carbon. If anything, they enhance the case for a market – it is in just these cases of unexpected changes that markets are able to allocate goods to their highest use, and find goods at their least cost.

Given our focus on vegetation and soil sinks, we review here some of the evidence on the interaction of management and nature as it affects carbon. The intent is to illustrate the magnitude and nature of these interactions rather than to assess them comprehensively. Understanding these issues leads to some practical guidance on how to include sinks in a carbon trading system. Among the important features we identify: (i) the effect of management can be extremely site-specific; (ii) carbon storage is highly variable from season to season as it depends on weather even if management is unchanged; and (iii) earth system feedbacks blur the line between nature and human action. Here we rely on previously published results or results from models that have been previously published.

8.3.1 Management effects

The site-specific nature of carbon storage is illustrated in Fig. 8.1 simulating the Terrestrial Ecosystem Model (TEM) (Melillo *et al.*, 1993; Xiao *et al.*, 1997, 1998; Tian *et al.*, 1999, 2003; Felzer *et al.*, 2004, 2005) for two sites and under three man-

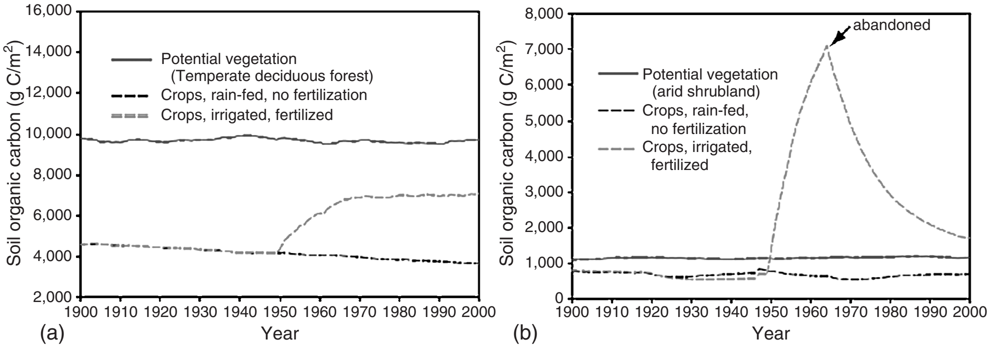

Fig. 8.1. Simulated historical changes in reactive soil organic carbon (RSOLC) at agricultural sites in (a) Buffalo, New York, and (b) Bakersfield, California, under three hypothetical management scenarios. Note that fertilizer application did not occur until 1950 in the fertilized scenario and that cropland at the Bakersfield site was abandoned in 1965.

agement regimes. Several observations are worth making. First, simulated reactive soil organic carbon (RSOLC) based on natural conditions (potential vegetation) varies by an order of magnitude between the sites. The arid Bakersfield site holds only about 1000 g RSOLC per square meter (g C/m^2), whereas the Buffalo site under natural conditions was estimated to hold about 10,000 g C/m^2.[1] Second, cropping was estimated to significantly reduce carbon storage at both sites, but the reduction was far greater at the Buffalo site in absolute as well as percentage terms of RSOLC. Third, while it is often assumed that the difference between the carbon in currently degraded soil and that prior to degradation represents the potential amount of carbon that could be stored, that difference is largely irrelevant to estimates of increased storage when a different management practice is applied. In particular, the Buffalo site with the addition of fertilizer and irrigation only gains back somewhat more than half of the RSOLC lost when converted to crops. In contrast, irrigation and fertilization leads to an increase in RSOLC at the arid Bakersfield site several times that under natural conditions. Fourth, as illustrated for the Bakersfield site, if management is removed, carbon storage can change substantially. In this case, much of the modelled increase in RSOLC due to irrigation and fertilization was lost in just a few years once the site was abandoned. Interestingly, it appears that some of the additional carbon stored may remain even after being abandoned for as many as 35 years. Even though it fell after abandonment, RSOLC remained on the order of 80% above the natural level. The management regime (and abandonment) was set to represent the actual historical management at these sites. Abandonment of cropping at the Buffalo site would likely lead to a further increase in carbon, perhaps back to near the predisturbed level. Other management practices alone or in combination may lead to other results, but our conclusions from just these two sites are that the impact of different management practices on carbon storage can differ by an order of magnitude, and that the 'predisturbed' soil carbon level is not always a clear guide to how much carbon could be stored.

8.3.2 Annual variability

Figure 8.2 shows total carbon in vegetation and its allocation among plant parts from a TEM simulation for maize for a site in China for two different years, a wet year (1995) and a dry year (1997). Here we see the substantial difference in carbon accumulation for two different years driven by the different weather conditions. Carbon in each plant part accumulated over the season in

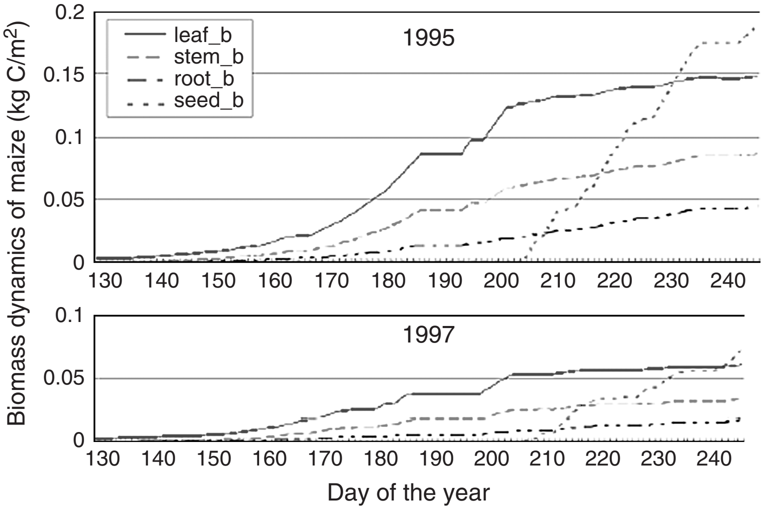

Fig. 8.2. Simulated carbon allocation among major plant parts using the Terrestrial Ecosystem Model (TEM) for maize grown in a north-eastern site in China (117° 12′ W 39° 06′ N). Actual daily climate data for a wet year (1995) and a dry year (1997) were used.

the dry year is only about half that accumulated in the wet year, with the difference in seed even greater.

8.3.3 Separating human and natural changes

Figure 8.3 illustrates a simulation of the different sources of change in carbon storage from 1950 through 2000 for the USA. Felzer *et al.* (2004) estimated that the USA was a net carbon sink but there were multiple factors, some offsetting and others interacting, that explain the net effect. The factors involve feedbacks from natural systems, natural variability and those that could be attributed to direct management. For example, land-use change and fertilization of crops (with nitrogen) are related directly to management decisions. Climate, shown to have a varying effect, is both naturally variable and may be changing because of human influence – sorting how much is natural variability and how much is due to human influence is a complex issue and not completely resolvable, particularly at smaller scales. Here the scale is near continental, but to create incentives for carbon management the scale needs to be at the level of parcels owned by specific individuals or companies. Increased tropospheric ozone damage is mainly due to increased precursor emissions from anthropogenic sources but these emissions are from energy use, over which the forest or farm manager has no direct control. Note that Felzer *et al.* (2004) also show an interaction effect between nitrogen fertilization and ozone damage: there is increased damage from ozone when there is nitrogen fertilization, that cannot be attributed to management alone or to the earth system feedback alone. In general, interactive effects are likely to be more important at smaller scales. The type of vegetation grown will interact with climate and CO_2 concentrations. When there are fundamental interactions of this type it is not possible to clearly attribute carbon changes to one or the other factor. Thus, attempts to base policy on whether the change in carbon is due to direct management, natural variability or some indirect anthropogenic factors are futile.

We clearly have a complex policy environment and a complex natural system with multiple feedbacks and interactions

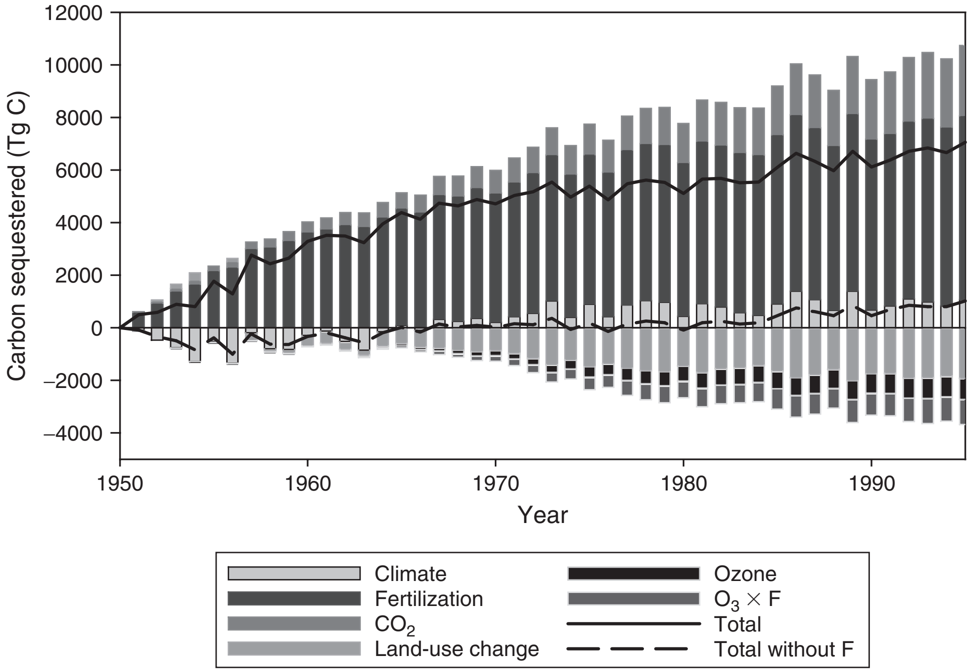

Fig. 8.3. Simulated effects on carbon storage in the USA attributable to different sources. (From Felzer *et al.*, 2004.)

between management and nature. Is there a way out of this complexity? We turn now to imagining how a very simple emissions trading system could work, if we could escape the inertia of recent negotiations and policy thinking and add some more information on the rough magnitude of sinks potential.

8.4 An Idealized CO_2 Cap-and-trade System with Land Use Sinks

Table 8.1 depicts a completely fictional situation in two imaginary countries. Both have the same fossil fuel CO_2 emissions in 1990 and the same projected level of fossil fuel emissions in 2010, a year chosen to be representative of the Kyoto commitment period. Country A is a large net land use sink, and country B is a moderate land use source. In the absence of any policy, country A's sink is projected to rise and country B's land use source is also projected to rise. If we imagine a hypothetical Kyoto-type target of returning to 90% of 1990 emission levels, we can see that in this example the target is different when we apply it only to fossil emissions or to total net fossil and land use emissions. Looking at the row labelled 1, country B appears to gain by including land use emissions because its allowance level based on total net emissions is 99, up from 90, when only fossil emissions are included. Country A gets only 72 allowances compared with 90, and therefore looks worse off with the total CO_2 accounting. But comparing the projected situation in 2010 as shown in the row labelled 2, it is actually country A that benefits from the total accounting because it needs to reduce only 23 below projected reference (compared to 30 if applied only to fossil fuels), and country B that is worse off, requiring a reduction of 41 with the total accounting compared with 30. This occurs because in the absence of any policy, sinks are projected to increase in country A, thus reducing the need to lower emissions or further enhance sinks.

In country B, however, the land use source is growing, thus putting more pressure over time to reduce emissions or increase uptake to offset the land use source.

What if, instead of the sink and source growing in these countries, it was projected to fall to a zero net sink and source? The reduction for country A from projected 2010 net total emissions would then be 48 in the total accounting example if they needed to return to 90% of 1990 emissions, whereas for country B the required reduction would be 21.

The first lesson is that moving from a fossil-only accounting to a total accounting including both land use and fossil emissions does not necessarily benefit the country that gets more allowances or the country with the large net sink in the base year. What is important is whether in the absence of policy the land use sink or source is projected to grow or to reduce.

The second lesson is that including sinks in a total accounting framework does not necessarily lower the real reduction. In the situation portrayed in Table 8.1, including sinks results in a real reduction below reference, totalling across both countries, of 64 compared with only 60 if sinks were excluded. Net emissions to the atmosphere in the fossil-only case in 2010 are country A (90 – 25) + country B (90 + 20) = 175, with the total accounting net emissions restricted to country A (72) + country B (99) = 171. In other situations, which readers can invent if they desire, total accounting could lead to an increase in net emissions.

The third lesson is that any effect on net emissions to the atmosphere due to the inclusion of land use sinks can be eliminated by adjusting the target reduction. If one has a projection of land use emissions for 2010, it is easy to calculate an adjusted percentage reduction from 1990 that will lead to exactly the same 'reduction of 30 from reference' in 2010 for each country with a total accounting. Adjusted percentages below 1990 (0.81 for country A; 1.00 for country B) are simply 2010 reference emissions less the 30 reduction from 2010 estimated in the fossil-only policy and then divided by the 1990 total net emissions. This results in a 'differentiated' reduction percentage for the two countries. Even though they are identical in terms of fossil emissions, differentiation occurs because they differ in terms of land use emissions. This assumes that the total reduction of 60 and the equal split of 30 in each country had some special merit.[2] The calculation depends on having a pro-

Table 8.1. Two hypothetical countries' fossil and land use carbon, 1990 and 2010. Relative units are given.

	Country A	Country B				
	Fossil emissions	Net land use emissions (+) or uptake (–)	Total net emissions	Fossil emissions	Net land use emissions (+) or uptake (–)	Total net emissions
1990	100	–20	80	100	10	110
2010 Reference	120	–25	95	120	20	140
Allowance allocations and real reductions: fossil-only compared with total net accounting						
1. Hypothetical target of 0.90 of 1990	Fossil-only		Total net	Fossil-only		Total net
	90		72	90		99
2. Reduction from 2010 projected emissions	30		23	30		41

jection of net land use emissions, and so one could argue that you cannot be sure you would get the same reduction in both cases because of this uncertainty. However, the same differentiation concerns arose for fossil emissions where there were recognized differences in projected growth among countries, and those projections were also highly uncertain at the time the targets were set.

To implement a trading system that operates among private parties the countrywide allocation must be distributed to private parties. This raises some additional issues about the implications for land use owners participating in a cap-and-trade system that often seem not well understood. We have thus invented, in Table 8.2, another hypothetical situation, focusing on the domestic situation in country A. Here we imagine two fossil fuel users with identical emissions in 1990, and two landowners: one with net sequestration and one that is a net source. One of the fossil fuel emitters has a projected decline in emissions in the reference for 2010 while the other's reference path will increase substantially. Landowner 1 remains a sink but the sink declines, while landowner 2, a source in 1990, becomes a small sink in 2010.

It is almost inevitable that the gross sink amount in the country (adding together the sink for only those landowners or parcels that are net sinks) is much greater than the country's net sink amount. Earlier, we used the example of the estimated 902 million tonnes as the annual net sink in the USA to illustrate how that could be used to offset US emissions. If one keeps to the simple strategy of measuring all terrestrial sinks and sources, the net sink is the offset. Much of the discussion of sinks credits, at least in the USA and Canada and as expressed in the Kyoto Protocol, focuses exclusively on credits for carbon uptake. This leaves out of the programme those landowners who

Table 8.2. Hypothetical situation for emissions sources and sinks in country A, with a target of 0.90 reduction from 1990 below total net emissions. Units are arbitrary.

	Fossil source 1	Fossil source 2	Landowner 1	Landowner 2
Emissions in 1990 and reference emissions projections for 2010				
1990	50	50	–40	20
2010 Reference	40	80	–20	–5
Possible allowance allocation, within parentheses required reduction (+) or excess allowances (–) that could be sold				
1. Grandfather to 1990 with proportional reductions	45 (–5)	45 (35)	–36 (16)	18 (–23)
2. Estimate 2010 reference with proportional reductions	30.3 (4)	60.7 (4.5)	–15.2 (–4.8)	–3.8 (–1.2)
3. Proportional responsibility from 2010 reference	33.6 (6.4)	67.4 (12.6)	–23.2 (3.2)	–5.8 (.8)
4. Credit for 1990 baseline sink, proportional reduction for all sources from 1990	30 (10)	30 (50)	0 (–20)	12 (–17)
5. Credit for any sink in 1990, allowance to match any land use source, proportional reductions for fossil sources from 1990	26 (14)	26 (54)	0 (–20)	20 (–25)

are net sources. If that is the background, the amount of sink credit is not limited by the net sink but by the gross sink amount, which is a much larger number. The gross sink amount is not even well defined unless the parcels of land are well defined and unchanging over time. In the example of Table 8.2, consider the possibility that landowner 1 has some land that is a net source, emitting 20 annually in 1990. To have a net sink of 40 in 1990, the remaining areas are thus a sink of 60. If there is an incentive to count only net sinks, landowner 1 might sell the parcel that was a net source, and thus get credit for 60 instead of 40. The ability to divide parcels into sinks and sources is nearly fractal in nature, making the potential gross sink huge.

This issue of deforestation is not ignored in the Kyoto Protocol – reducing deforestation is a potentially creditable action – but the failure to include the entire terrestrial biosphere in tracking compliance with the policy targets creates problems. There is an incentive for those who might reduce deforestation or who have sinks or might increase them to register credits, depending on how the baselines are established, but no accounting in compliance with the target cap of those that are likely to remain a source or become a bigger source. Lack of full coverage creates the problem of leakage – reductions among credited sinks being offset by increases in non-covered land areas. However, allowing landowners to voluntarily register credits when it is in their interest worsens the problem because it is almost certain to enlist mostly those who intended to increase sinks anyway, while producing no incentive to control for those who had intended to become a large source.

In the second part of Table 8.2, some hypothetical allowance allocation principles have been considered. Supposing that a cap would cover terrestrial biosphere sources and sinks as well as fossil emissions. The common implicit assumption in most discussions of sinks allowances is that one can only cap sources, not sinks. Of the five allowance allocation principles in Table 8.2, the first two do not distinguish between sources or sinks in setting allowances, i.e. they give no special consideration of the zero point on the number line.

Principle 1 is essentially the Kyoto allocation rule as applied to a country's emissions, used to allocate the allowances among entities within a country and including both fossil sources and land use owners. Like the Kyoto national allocations, it uses 1990 as a benchmark and allocates the reduction to individual entities proportionally – country A's target is 90% of 1990 net emissions, and thus each entity receives an allocation proportional to its 1990 emissions and/or sinks. For the land use source, this is a reduction of its emissions to 18 from the 20 in 1990. For the land use sink, the allocation is –36 compared with emissions of –40 (i.e. a sink of 40 in 1990). Rather than getting an allowance of zero, 40 more than it 'needs' as of 1990, landowner 1 starts in a debit position but at least as of 1990 there was enough sink to cover this debit (and indeed an excess). The very different rates of growth of emissions and changes in sinks for the 2010 reference conditions reveal the same issue that has plagued the Kyoto national allocations. If the targets are undifferentiated, these different expected growth rates lead to very different burdens. So even though the Kyoto allocations refer to 1990, differentiated reductions for individual countries take into account to some degree expected differential growth in emissions. Here we see that allocation principle 1 results in very different required reductions for individual entities. Fossil source 1 and landowner 2 have allocations well above the projection of reference emissions. They could sell these allowances, and probably reduce further at low cost and sell even more. The burden of buying permits would fall on fossil source 2 and landowner 1, even though landowner 1 is a large sink. How big this differential growth effect can be obviously depends on how differently emissions and sinks are expected to change for different entities.

Allocation principle 2 corrects this differential growth problem by making the allocations proportional to the projected reference for 2010. This reveals a different issue that arises with simply multiplying the base by 0.9. The mathematics works to produce the right national cap of 72 but the rule means that any entity that is a sink will necessarily have excess credits to sell, and this occurs for both landowners in this example. The algebra of this reduction is

$$\text{National target} = \%\text{RED} * \text{EMISS} + \%\text{RED} * \text{SINKS} \quad (8.1)$$

where %RED is the required national reduction from reference, EMISS is emissions from fossil sources and SINKS is net emissions (sink or source) from land use.

Allocation principle 3 seeks to make the burden of reduction proportional to the level of emission source or sink by altering Eq. 8.1 slightly:

$$\text{National target} = (1 - \%\Delta) * \text{EMISS} + (1 + \%\Delta) * \text{SINKS} \quad (8.2)$$

Knowing the national target, projected emissions and projected sinks, one can then solve this for the %Δ. This formulation simply generates an allowance allocation that, without trading, would require sources to proportionally reduce their emissions and sinks to proportionally increase their sink. For the example we have created %Δ = 0.159. Emissions sources get an allowance that is 15.9% below projected reference emissions, and sinks get an allowance debit of 15.9% more than their projected sink. This again leads to an allocation that meets the national cap, but now no entity has allowances that would allow them to sell credits without taking some additional action beyond what is projected to occur in the reference. Each entity bears a 'proportional' burden.

This formulation is far from perfect. Note that landowner 2 has a small net sink, and so the equiproportional change results in a small absolute change. Consider a landowner who coincidentally is at zero, neither a source nor a sink. This landowner would get away without any burden, even though he or she may be in a position to become a significant sink without much effort. At first look, this is not so different from the problem faced by fossil emitters – reductions may be costly and difficult for one and easy for another, and so equiproportional reductions need not imply the same cost burden. However, for landowners it is not unreasonable to imagine an owner of 100 acres and an owner of 1,000,000 acres. If the latter coincidentally has zero net emissions, no burden exists under this allowance principle. Yet, other things being equal, there would be much more scope for increasing sinks on the 1,000,000 acres than on the 100.

The principles for allocation rules 4 and 5 are closer to what appears to be the view of the land use community. The implicit equity principle is that coincidentally being a sink means that one should be able to sell all of the sink allowances. In both of these, landowner 1 gets zero allowances rather than a debit as in allocation rules 1–3. Even though this entity's sink is declining, he or she has allowances to sell even without reversing the decline. Allocation principle 4 treats the landowner source symmetrically with the fossil emission source, requiring a proportional reduction in emissions. Again, however, the zero problem is likely to occur. Big landowners with a source approaching zero would have a very small required reduction, with the potential to easily become a large sink. This could be considered an asymmetric treatment with that of fossil emitters but it is a symmetric treatment with landowner 1, the net sink. Being a net source is villainous, but crossing zero on the number line makes you virtuous with a generous allocation of allowances as your reward.

Allocation rule 5 further distinguishes between land use emissions and/or sinks and fossil emission sources by granting landowner sources an allowance equal to their emissions. This is closest to the implicit assumption that landowners would enter a programme voluntarily and have no burden to reduce unless they chose to do so. Thus, landowner 2 could do nothing to change his or her land use emissions, and still would not have to acquire additional allowances. While on the face of it, this is close to current policy approaches to include sinks via a credit system, capping landowner 2 is actually far better. While he or she gets allowances equal to expected emissions requiring them to do nothing, emissions cannot increase without acquisition of permits to cover them. Thus, it prevents spatial leakage, at least within the countries that follow this policy. Of course, the more allowances one grants to landowners, the more the burden shifts to fossil sources. Allocation rules 4 and 5 used 1990 conditions as the basis for establishing allocations. The same principles could be applied to reference 2010 emissions as in allocation principle 2. We are not proposing that one or the other of these allocation rules is preferable, but use these examples to illustrate that there are a number of ways to extend simple allocation principles that might be used for fossil sources to terrestrial carbon sources and sinks with very different implications for burden-sharing.

The problem Kyoto negotiators ran into was that they agreed to the burden on fossil emission reductions first. They then needed to produce language and processes to make sure that sinks credits would really be reductions beyond a baseline; otherwise the situation in which 'hot air' from sinks credits might cover all emissions increases would have been a distinct possibility. As the negotiations occurred in the run-up to signing the Kyoto Protocol in 1997, because they had little data on sinks in 1990 or projected levels in 2010, it was impossible to adjust the allowance levels to take these into consideration. At the time, the chosen approach – caps on fossil emissions and sinks allowed in as credits against the cap – was perhaps the best that could be done. The approach, however, has left us with a legacy of poorly defined categories of land use activities.

A reading of the views of the community that usually discusses sinks and sees profit in them is that they envision allocation rules like 4 and 5. The moral premise for getting this windfall gain appears to be that sequestering carbon is virtuous and it should be rewarded. However, the main reason the uptake is now occurring is that in the past history of this land, deforestation or tillage practices occurred that released carbon. So today's virtue is only erasing yesterday's vice. Thus, most people would not automatically find allocation principles such as 4 and 5 compelling. These are issues of equity or relate to perceptions of what is fair. Potentially being forced to buy additional allowances even though a landowner is a net sink would no doubt strike some as unfair. The issue of credit for past actions is one that also affects combustion sources, whereby firms would like to get credit on the basis of having adopted less emitting practices before adopting the policy. At the start-up of a programme there is an incentive issue beyond the fairness issue: if allocations are based on actual performance in years before the start of the programme, as they have been in most cap-and-trade systems, firms would have an incentive to perform poorly up to the start of the programme or risk receiving a small allocation based on low emissions. Thus, there is some basis for giving such credits to encourage early action, but determining a baseline is difficult. If one begins applying such early action credits, it only makes sense to maintain 'policy neutrality' so that every credit given for past action is balanced by tightening the overall cap. At least one must recognize that generous crediting for prior action may mean that a cap will not achieve the reduction originally planned.

One issue that affects perceptions of fairness with regard to sinks allowances, however, is that any sink is likely to be temporary. Thus, if a landowner receives a permanent annual allocation requiring it to be a permanent sink, eventually it will not be possible to achieve uptake at that level. The landowner would thus need to purchase permits indefinitely even if carbon levels were fully restored to a natural state (or higher through permanent management). Such a permanent liability does not necessarily create an economic inefficiency. The lump sum (negative) allocation would result in a drop in the value of the land reflecting expectations of the cost of the permanent liability, just as a generous lump sum allocation would result in an upward value of the land reflecting the fact that the landowner could have permanent income from the sale of allowances. It should then not affect future production decisions. If one wishes to correct perceived unfairness, one solution is a one-time negative allocation, with an annual requirement of no emissions. The one-time allocation could be based on the difference between an estimated 'steady-state' carbon stock under 'good' practices and the current carbon stock under degraded conditions. The landowner could work off this negative allocation by following good practices, and after that would only need to maintain the stock of carbon.

In showing various principles by which a cap-and-trade system could be extended to sinks and sources related to land use, we have hoped to demonstrate that there is no reason why sink needs to be treated in a widely different manner as a fossil source. A target can be fashioned to achieve the same net effect on the atmosphere with land use sinks and sources included as when they are not. To do so requires an adjustment in the cap level to account for the net land use sink or source, and given different changes over time among countries or entities, their inclusion can have potentially large effects on burden-sharing that can be overcome through differentiation or choice of allocation rule. Blindly excluding land use emissions and sinks, or giving landowners the choice to voluntarily sell credits or not does not make these issues go away. It only eliminates or limits economic incentives to reduce emissions or increase sinks in the most cost-effective manner.

With this idealized system laid out, we turn to issues that have been the subject of considerable investigation regarding the inclusion of sinks with the goal of identifying which of these remain an issue, and which of them largely disappear when the policy architecture is better formulated.

8.5 Sinks Issues in Policy Discussions

As noted previously, a confusing array of issues related to the inclusion of sinks in a climate mitigation policy has arisen. The Intergovernmental Panel on Climate Change (IPCC) brought out a special report providing a good compendium and a full discussion of these issues (Watson *et al*., 2000). It is structured and hamstrung, however, by the policy environment and governmental interests to which it was reporting. In trying to be comprehensive and responsive while avoiding to be policy-prescriptive, it is not as effective as it could be in sorting out reasonable approaches and strategies from those that create problems rather than solve them.

8.5.1 How much to pay for an additional tonne of sequestration compared to an avoided tonne of emissions?

Many issues have been wrapped into this question, and various solutions proposed. Some would like to pay landowners up front for prospective storage once a forestation project has been established. Worried that the carbon may not remain stored, the concept of 'discounted' tonnes has been created, whereby a fractional discount factor would be applied to account for possible return of carbon in the future – leakage. Others have proposed renting carbon storage – paying a price per tonne-year stored so that if the landowner chose to do something differently in the future, he or she could do so and would have received payment only for the time they actually stored the carbon. This is a solution to the problem of paying for a 'permanent' tonne only to have the landowner abandon the activity that is keeping it sequestered. Many of these approaches are based on solid economic analysis, recognizing that carbon storage is an investment problem, and can be analysed using the same formulas as for any investment. McCarl *et al*. (2005) and Lewandrowski *et al*. (2004) provide good reviews of different approaches.

Key to investment problems is the net present value (NPV) of the stream of returns. A landowner considering a sequestration project would compare the NPV of carbon storage to the investment cost plus the discounted stream of annual maintenance costs, just as he or she might compare the NPV of returns to installing irrigation to enhance crop production or establishing a forest for purposes of harvesting the wood. Herzog *et al.* (2003) offer one formulation of this NPV problem:

$$\mathrm{NPV} = p(0)a(0) + \sum_{1}^{\infty} p(t)a(t)(1+r)^{-t} \quad (8.3)$$

where $p(t)$ is the price of carbon in year t, $a(t)$ is the net amount sequestered or leaked in year t and r is the interest rate. They use the formulation to estimate a discount factor for ocean sequestration, imagining that the carbon would be sequestered in year zero and would gradually return to the atmosphere over a very long time. Thus in their problem $a(0)$ is positive and $a(t)$, for $t = 1, \ldots \infty$, is negative. The same approach has been proposed for land use sinks, and for conceptual purposes the time periods could be of a length where all sequestration occurred in period zero – e.g. each period could be 10, 20 or 40 years – and leakage then might occur in later periods.

The simple and economically efficient approach for pricing carbon is to allow the market to price it once a cap has been established. A landowner who sequesters a tonne of carbon in period t may choose to sell the tonne at the full market price in time t or could hold it for future use or sales. Should the landowner at time $t + n$ emit a tonne of carbon back into the atmosphere, he or she would then be responsible for purchasing a carbon allowance at the going price in year $t + n$ or could use the banked tonne. This treatment is symmetrical to that of a fossil fuel emitter, say an electric power producer, who might be considering different power plant options that would have different streams of carbon emissions in the future. If the carbon stream were less than the allowance stream, the power producer could sell the extra allowances into the market or bank them against the possibility that it may not be of interest to continue the operation of the carbon-saving power plant indefinitely just as the landowner might decide to change his or her land use practice in such a way that carbon previously sequestered is released. The zero point on the axis, going from sink to source, has no special meaning in this trading environment. All that is important is how an entity's emissions or uptake compares with its baseline allocation of allowances so that it can determine whether it has allowances to sell or must acquire allowances.

Alternative solutions whereby there is an established rental price or an established discount for land use sinks lead to potential economic inefficiencies by asymmetrically treating fossil emitters and landowners. If we knew for certain future carbon prices and market rate of returns, and which sinks would leak at which rates, or at least the average leakage rate, one could establish an equivalency between rental rates, the carbon price and a discount factor.

Herzog *et al.* (2003) calculate the discount factor by calculating the NPV as in Eq. 8.3 and dividing it by the NPV of permanent storage (i.e. when $a(t)$, for $t = 1, \ldots \infty$, is zero). Lewandrowski *et al.* calculated a rental payment as

$$a = rP \quad (8.4)$$

where r is here the discount rate and P is the price of a tonne of permanently sequestered carbon. This result is derivable from a formulation like Eq. 3 under some highly simplified assumptions, namely that the price of carbon is constant over time. As Herzog *et al.* (2003) show, if the price of carbon rises at the rate of discount, the value of temporary storage is zero, and there are conditions under which we might reasonably expect the carbon price to rise at that rate. In particular, with a stabilization target and no backstop, efficient allocation of the reduction through time would require a constant discounted price – i.e. the actual price rises at the discount rate. We would not press the case that actual carbon price will necessarily rise at the discount rate but use this example to illustrate that the rental rate for carbon depends on what you assume about the future carbon price path – and, under some not implausible assumptions, the right rental rate could be zero.

The various formulations of: (i) sell or buy permits as you go, (ii) discounted tonnes, or (iii) renting carbon are all derived from the same basic formulation and so it would seem that any of these options could be used. Although the mathematics can be manipulated to derive one formulation from the other, problems arise because:

1. Calculating the discount factor or the rental price requires someone to know or estimate future carbon prices and the appropriate discount rate. If a public agency is to compute the discount factor or the rental value, they must make some projection of these.
2. Whether and when leakage occurs is not purely a phenomenon of nature that occurs with a known (or knowable) frequency, but rather is at least partly under the control of the landowner.

Problem 1 indicates that the public agency bears the risk of being wrong with rental calculations or with the discounted tonnes calculation, whereas when the fossil emitter's investment decisions require forecasting, the risk is on the private entity. One can make a case that the public agency should take steps to limit risk to private entities, but there is no good reason to have some segment of mitigators (fossil emitters) bearing the risk, and another segment (land use sequesters or emitters) not bearing the risk. Problem 2 indicates that an upfront discounted payment with no requirement to be responsible for the future of the carbon creates no incentive for the landowner to take actions that would prevent return of the carbon to the atmosphere. The rental formulation partly avoids this by only paying as you go, but because it produces incentives for sequestering but not avoiding emissions, it leaves land use emissions uncapped.

The 'disconnected tonnes' makes carbon sequestration less attractive – those landowners who might be willing to assure that the carbon had been permanently stored will be less willing to sequester at a discounted payment. If leakage were a purely natural and random phenomenon with no ability to know what its rate was for a specific parcel or to control it, the discount approach would on average credit the right amount. Since with these assumptions the landowner had no control over leakage, the lack of incentive to control it has no effect on leakage. However, these are unreasonable assumptions. The landowners who, a few years after accepting the payment, decide to do something else face no penalty for releasing the carbon. Realistically a programme of upfront payment would likely include conditions that would limit the landowner's actions, or penalize him or her for actions that led to sequestered carbon being emitted. But the efficient penalty is for the landowner to purchase carbon permits at the going price at the time the carbon is emitted. The notion of a penalty – that a wrong was committed – is mischaracterizing the decision. Simply allowing the landowner to essentially buy out of the commitment to store the carbon by purchasing credits preserves the option to use the land in another way if it is more economic. From a broader economic standpoint, preserving this option makes a lot of sense. If for some reason food is short and agricultural commodity prices rise, the landowner can switch to crop production. As long as carbon allowances are purchased to cover the emissions, the country will continue to be in compliance with its GHG mitigation targets; yet it allows land to be used to solve another pressing problem, food supply. There is no net leakage that is not covered by a reduction in emissions (or more uptake) elsewhere, and so there is no need to apply a discount to sequestered tonnes in the first place.

We have been careful to identify problems with tonne-years and discounting as a problem of a public agency implementing these formulas. All of the market approaches we see in capital and investment markets are likely to develop in a carbon market if it is set up as we propose – selling when sequestering at the then current price, and requiring allowances to cover emissions if at some point the carbon is released back to the atmosphere. In particular, landowners who wanted an upfront payment would probably find intermediaries prepared to pay some amount for the future stream of sequestration. The payment would reflect the intermediary's expectations of future prices of carbon, and a contract would need to be structured to describe who would bear the risk if the landowner was later found not to have sequestered the carbon. For this system to work, this requires that the sequestration agreement is legally enforced and the sequestration is monitored over time by a public agency. Landowners might simply bank credits they have created through sequestration, speculating that the price might increase and leave them in a difficult financial position if they wanted to do something that would release the carbon. Future prices and future contracts would likely develop, and intermediaries may be willing to rent carbon based on their speculation of what such temporary storage was worth – i.e. speculating on how carbon prices would change. Contracts and agreements between landowners and such intermediaries could be negotiated or might vary depending on the interests of the landowner, and the risks the intermediaries were willing to accept. In short, the market would quickly invent solutions to illiquidity or the need for upfront payments to cover investment, at a price, just as it has for other investments. Many concerns about the ability of landowners and markets to deal with carbon pricing over time have been expressed in the literature. However, investing in a forest for the sake of receiving payment in the future for the carbon stored is no different than the problem of investing in a forest with the goal of selling the timber in the future.

8.5.2 What should be done about the possibility of catastrophic release of carbon or the high variability of ecosystem uptake?

The amount of carbon taken up by plants varies dramatically from year to year depending on the weather. Rapid growth in one year may produce a lot of litter subject to rapid decomposition, and if followed by a year of poor growth, the result may be net emissions that year, with decomposition release greater than the carbon taken up by new growth. Wildfires might lead to large net emissions that would destroy well-meaning efforts to sequester carbon, and are the most dramatic example of catastrophic release evidently beyond the control of the landowner. However, these natural phenomena that lead to variability again would seem to be no different from the normal situation landowners face. Bad weather that leads to little carbon uptake, and possibly net emissions, is no different to the situation where bad weather leads to crop failure and financial loss because there is no revenue to cover the cost of planting and other costs of farming. Similarly, the forest manager who had planted a forest in anticipation of harvesting the timber faces potentially catastrophic loss if there is a forest fire that wipes out the young forest. Limiting financial liability for these risks in the case of carbon storage would limit the incentives landowners would have to take actions to limit the effect of these events. The prudent landowner would enter into carbon sequestration with the same set of risk calculations he or she would use in cropping or timber management, taking into account an estimate of the variability over time of carbon uptake. This might include carrying a bank of credits from good years to cover bad years, the use of various financial instruments to cover the risk (saving, insurance, forward options on purchase of allowances to cover potential risks) or fire prevention and weather amelioration strategies (irrigation) that would limit the effects of these natural conditions.

One element of the variability issue deserves some consideration. Public monitoring and enforcement will need to create a periodicity to inventory requirements. It is not likely that land use carbon would be 'continuously monitored' and the concept is almost nonsensical given that carbon is exchanged continuously through the day and seasons with periods of net uptake and net release. The preferred method is likely to be to estimate a stock at time *t*, re-estimate the stock at some later time, and the difference is the net uptake or release. So there is a decision to be made as to how often that inventory must be updated and reported.

The Kyoto Protocol set a 5-year commitment period for countries, essentially allowing unlimited borrowing and banking within that 5-year period. Countries may require fossil emitters to provide inventories more frequently – e.g. annually. Because of the variability of land use carbon, the difficulty and cost of accurate measurement, as well as the likely approach of measuring the stock instead of the continuous flow, it likely makes sense to have a longer rather than shorter required inventory periodicity for land use carbon. This would automatically allow borrowing and banking over the established period by the landowner. For example, if an annual inventory period were required and the landowner had to be in compliance with the target each year, and if the first year was a bad weather year (or unluckily a forest fire struck), the landowner might be required to make a big purchase of allowances, only to have large net sequestration in subsequent years. This is not insurmountable; explicit banking and borrowing provisions could be created such that this variability could be evened out. However, inventory methods are likely to involve some cost, and may not be accurate enough to reliably measure year-to-year changes. This suggests that the goal may be to set the periodicity of the inventory at least every 5 years and possibly as much as every 10 or 20 years.

It does not seem essential that the periodicity be the same as either a national target period such as in the Kyoto Protocol or the same as for fossil emitters. If, however, one requires that allowances can only be used once the carbon is actually sequestered, and has been certified as such, this could mean that no sequestration could be credited until the second inventory was taken, perhaps 20 years later if that was the official reporting period. This does not present any fundamental problems, but for those hoping to use sequestration in early periods this would prevent it. Not to make too much of this constraint, it would not necessarily mean that landowners could not find intermediaries who would pay them early, on an intermediate assessment of carbon sequestered, and on an expectation of future carbon prices. However, one way to add flexibility without necessarily requiring frequent and costly inventories would be for the reporting rules to allow landowners to inventory more frequently. If they followed established principles, sequestered carbon could be credited in the current period. For example, a landowner might choose to inventory and report after the 5th year, even though only required to do so once every 20 years.

8.5.3 How to resolve the problem of determining direct human responsibility for sequestration?

The Kyoto Protocol limits sinks credits against targets to those due to ‘direct human-induced . . . change’. In retrospect, this may be among the most problematic passages on sinks in the agreement. As we reviewed in Section 8.3, strong interactions of nature and management mean clearly that separating carbon uptake into these two categories is impossible. Felzer *et al.* (2005) estimate the tropospheric ozone damage effect to be substantial, and while the extent remains controversial, CO_2 fertilization as usually modelled strongly enhances vegetation growth and carbon uptake. Climate change itself will affect plant growth. These are probably what the framers of the Protocol considered ‘indirect’ effects and thus meant to exclude. However, it does not seem as easy to dismiss the US interpretation, where simply protecting property rights is a direct human action that might lead to carbon sequestration, or at least prevent deforestation and carbon release.

Even if one were to take a very narrow definition of actions – a specific forest established with the express intent of sequestering carbon – and one could somehow assess ‘intent’, the ‘direct human-induced’ language would seem to require the ability to attribute some part of the carbon sequestered to the direct human action. It would mean subtracting out that due to indirect actions (nitrogen deposition, CO_2 fertilization), or even giving credit for more than was sequestered if some indirect action (e.g. tropospheric ozone) damaged vegetation which would have otherwise taken up carbon. One would need to at some level confront the reality that once trees are planted, it is mostly nature that takes over and grows them, and so the distinction of what is due to direct human action and what to nature or indirect action is necessarily fuzzy. In reality, vegetation growth is a collaborative effort of humans and nature, where the result is not uniquely attributable to either collaborator. Trying to create rules and then measure and attribute carbon uptake to different causes would seem to be a distraction, adding to the cost of monitoring and, if anything, creating cost inefficiency. With clear property rights for land, and the ability of the landowner to sell allowances for anything sequestered on it above the established baseline, or pay for emissions above (or sequestration less than) the baseline, that landowner (or the country in the case of national targets) has an incentive to fix the problems that lead to damage. Again drawing the comparison with forest and agricultural products, products harvested by the landowner can be sold and are not subject to a test of whether the products were 'human-induced'. The public good nature of the 'indirect' human effects such as air pollution requires collective action to solve, and including all carbon sequestration or emission within an incentive structure would not automatically solve these problems. But, with landowners losing or gaining depending on whether these other environmental problems are solved, it would at least provide a motivation for them to support collective action on pollution.

As previously noted, the concern of limiting sinks to direct human action as in Kyoto would appear to arise from the fact that negotiators focused first on emissions and reduction goals, and having agreed to those, tried to bring sinks into the format. With that approach, making sure sinks credits were for uptake beyond 'business as usual' was a necessary consideration. In retrospect, however, this gave rise to language that has proved nearly impossibly to implement. The problematic language could be avoided if the caps are reformulated as caps on total emissions from fossil and land use net of sinks. This will mean, however, rethinking the targets because, as shown in Table 8.1, a given percentage below 1990 emissions will have very different implications if applied to all emissions and sinks than if only applied to fossil emissions.

8.5.4 Broad cap or sinks as credits?

In the experience with emissions trading systems, two types of approaches to creating tradable emissions reductions are identified (e.g. Ellerman *et al.*, 2000). A cap-and-trade system distributes allowances that must then be used by entities under the cap to cover their emissions. Trading is among these allowances. However they are originally distributed, entities may purchase more if they need them or sell extras they do not need, but they must hold allowances to match their emissions. The second type of system is a credit system. In a credit system, credits are earned by reducing emissions below an established baseline. Typically, entering the credit system is voluntary: there is a market for the credits and it is in the economic interest of an entity to produce credits at the going price if they can do so, but other entities may choose not to enter the credit system and so they are not required to make any reductions. A credit system is often an add-on to an allowance cap-and-trade system. The cap-and-trade system forces the entities under the cap to reduce emissions whether or not it is economically desirable, and thus allowances have a positive market price. Those entities outside the cap but allowed to produce credits can sell credits in the market if they want to. Since producing credits is voluntary, no entity covered under the credit system should bear net costs unless they have miscalculated their own cost of producing the credits. Those under the cap can be shown to gain from trading (as compared with trying to meet the allocation without trading), but in most cases they are bearing costs compared with not having the policy at all. Trading is beneficial because it reduces costs. Of course, a generous allowance allocation can mean that even under the cap there may be some entities that benefit from the policy compared to the case with no policy, but if the cap is binding, the entities under the cap on average bear a cost.

The Bush Intensity target is voluntary, and its main aspect is a credit system. At present there is not much of a market for these credits, but producing and registering credits may be worth it if entities anticipate that there will be a cap-and-trade system in the future. The McCain–Lieberman Bill was a cap-and-trade, but sinks were allowed in as credits. The language of the Kyoto Protocol is one that would allow sinks in as credits at least in terms of a country meeting its target. It is not clear that this would foreclose sinks or some amount of land area entering under a cap within a domestic system of a party under the Protocol, but whatever the result of that broader cap, it would have to be squared with the sinks language in the Protocol, making them credits against the national cap. As already noted, a problem with a credit system is the 'real reduction' problem. A baseline for emissions, the reference against which credits can be earned, is hard to establish. If very loose, many entities may have an interest in entering the credit market as sellers but many of the credits may be unrelated to real reductions. If very tight, few will have an incentive to sell credits. As a result, much effort must be expended to determine the baseline for each entity with potential credits. In contrast, if the national allowance target can be established, the integrity of the overall target is not compromised even if the allocation provides 'hot air' allowances to some participants.

Both spatial leakage (landowners not voluntarily entering the credit system) and temporal leakage (landowners selling credits this period with the sequestered carbon being emitted in later periods) are a problem with credit systems. A forest landowner, who forgoes harvesting to sequester carbon, reduces the supply of lumber. But the demand for lumber remains, and so other lumber suppliers produce more lumber, thereby offsetting most of the sequestered carbon by higher emissions from forests not in the credit system. Leakage will potentially occur anytime the policy is incomplete spatially or temporally. Cap-and-trade systems that are not geographically comprehensive also suffer leakage, and if a cap-and-trade system were only going to be in place for a few years, one might expect temporal leakage in such a system as well. A well-structured policy that covers all potential emitters and sinks across space and over time eliminates the problem of leakage. A credit system in which coverage is voluntary does not assure this, whereas a cap-and-trade system can be easily structured to do so.

8.5.5 Permanence and leakage: a special problem for carbon sequestration?

Leakage is a concern for climate change as the cap that is set, presumably based on a solid assessment of acceptable emissions of carbon to the atmosphere, is not met because reductions taken by some entities are offset by an increase in emissions by entities not under the cap. As permanence is analogous to the spatial leakage problem, it is useful to refer to it as temporal leakage. Spatial leakage occurs because, at a given time, some emitters are not covered by the cap. Temporal leakage occurs when entities are induced to make reductions or sequester carbon in one period, but are outside the incentive system in a later period. Land use emissions face a special problem with permanence and leakage only because land use has been envisioned as entering voluntarily and as a credit rather than under a cap.

8.5.6 Ancillary benefits, pre-existing distortions

Equating marginal costs of carbon reduction and sequestration across the economy is an economically efficient solution in an idealized economy where all other prices appropriately reflect the real marginal cost of goods. Taxes, subsidies and unregulated externalities (positive or negative) result in prices not reflecting the full marginal cost of all inputs, and therefore an idealized policy that results in equating marginal costs of carbon reduction among countries or across sectors may not be the most cost-effective policy (Babiker *et al.*, 2004; Paltsev *et al.*, 2005). Ancillary benefits of both carbon sequestration and emissions reductions are often cited. Emissions reductions by fuel switching may reduce the emissions of many other air pollutants (Matus *et al.*, 2006). Carbon sequestration may reduce soil erosion and leaching of agricultural chemicals, thereby reducing water pollution (e.g. Marland *et al.*, 2005). Some fuels are taxed heavily in some countries (Paltsev *et al.*, 2005); many countries have significant agricultural subsidies. All of these externalities and distortions mean that equating carbon prices across sectors and economies is unlikely to result in the economic efficiency the simple textbook story suggests. The 'first-best' solution in economics literature in these cases is to work to get rid of the other distortions by appropriately pricing other externalities or to reduce the distorting effects of taxation. Where these distortions are and how to get rid of them needs research and policy attention.

We would argue, however, that we need to avoid the often first impulse of adding a mark-up or mark-down on carbon prices from activities with different pre-existing distortions or ancillary benefits. The danger of such mark-ups or mark-downs is that the ancillary benefits or extra costs are likely to vary by fuel (in the case of fossil emissions) and by particular site and sequestration option for land use activities. The correct mark-up or mark-down will also likely change over time. Thus, it seems preferable to work towards fixing the other problems directly, and pricing the 'partial interest' in the carbon mitigation options for its climate benefit. Recognizing and pricing 'partial interests' is not a new concept (see Wiebe *et al.*, 1996 for a careful discussion of pricing partial interests in land related to environmental goals). There may be reasons to make exceptions, but it seems preferable to keep the climate policy instrument clearly focused on climate policy rather than to use it to jointly solve a myriad other problems for which it may be a relatively poor instrument. Again the existence of ancillary benefits or costs is not unique to either land use sources or sinks.

8.5.7 Measurement, monitoring and enforcement

Much scientific attention is directed at developing and improving the reliability of techniques to estimate the stock of soil carbon at a particular time. This is important and essential work, and more progress is needed. There will, however, always be uncertainty and inaccuracy in these measurements. Measurement error need not be fatal to including carbon sequestration in a cap-and-trade system. A trading system can operate as long as the measurement process is accepted as defining an authoritative measurement – it need not be accurate with certainty. The process might include not only a technical approach to measurement but also the ability to challenge a measurement and a process for resolving questions or challenges, and final certification. While error in measurement can be tolerated, it would be hard to create legal authority if errors were so large and random as to appear to lack any scientific foundation.

A more subtle problem, however, is a compromise of the effectiveness of the system if there is a bias in the measurement process. If on average the measurement process systematically underestimates carbon stored, the system will provide too little incentive to sequester carbon, whereas if it systematically overestimates carbon, the cap will be met legally, given that the measurement system is legally accepted, but the effect on the atmosphere will be less than expected. This can be remedied by further tightening the cap to meet the atmospheric target, but carbon sequestration will be overused compared to emissions reductions because pricing does not reflect the actual carbon sequestered.

An even subtler problem of bias arises when a measurement process has been constructed to be unbiased based on experimental measurement, but the incentives to participate lead to bias in the actual application. Consider the following situation in which a practice is extensively evaluated through experiment and an average sequestration level is attached to that practice. The average sequestration achieved by the practice becomes a part of the measurement method – the part of the model by which carbon inventory is estimated. Under real conditions, the vigour with which the practice is implemented may be subject to variation. If it costs more to vigorously implement the practice, actual landowners may have an incentive to minimally implement the practice. This, in turn, results in less carbon stored on average under real conditions than the average experimental result. Another way this may happen is if the cost of implementing the option is correlated with an environmental condition that also affects the amount of carbon stored. If the correlation is such that lower costs are associated with lower carbon uptake, again the average uptake under real conditions will be less than the experimental average, because the activity will be implemented at the low-cost sites but it may not be economic to implement at the higher-cost sites. Reliance on practice rather than actual measurements tends to increase the chance of these incentive effects to create bias in the estimates.

Finally, enforcement is a necessary element of a successful system and must be part of the design. One of the surprising aspects of a cap-and-trade system as described by Ellerman *et al.* (2000) is that enforcement has been much more successful. There is no direct reason in economics for this, but rather it appears that regulators are more willing to enforce a cap when they can point to allowances that can be purchased to meet it. Since all entities have opportunities to purchase in the same market, the claim of some entities facing special hardships that prevent them from complying is less compelling. Hardship is more compelling in systems where entities must comply with an individual limit, and experience shows that exclusions are often granted, and so the environmental target is rarely met. Consider the case of wildfire that resulted in carbon emissions. If the landowner were required to meet some level of sequestration, and keep the carbon sequestered for some minimum period of time, enforcement in the face of fire becomes problematic. The landowner may have little ability to actually comply. The enforcement agency can levy a fine, but this can appear unreasonable given that the landowner could not prevent the fire. This would likely give rise to hardship exclusions. In any case, the carbon is in the atmosphere, and levying a fine would not remove it. With cap-and-trade, where the landowner can purchase or sell allowances, a fire is a hardship but the landowner can still comply by purchasing allowances.

Again, homeowners and businesses that choose to locate in areas prone to disasters mostly face the economic consequences of these disasters, and therefore presumably try to limit their exposure to, and the effects of, these disasters. The same principles should be applied to carbon sequestration. To the extent emergency aid or disaster assistance would apply to carbon losses, care is required to structure the aid so as not to undermine the incentives to reduce the chance of losing the carbon. Completely exempting the landholder from any responsibility to cover these emissions with credits would certainly undermine these incentives. One alternative worth further consideration that could provide some relief would be that if the landowner demonstrated effort to re-establish the forest and restore the carbon, he or she could borrow against that planned future replacement of carbon to cover the catastrophic loss. Such borrowing automatically occurs within the inventory period, and so a long period such as 20 years automatically gives the landowner a chance to restore carbon catastrophically released in, for example, year 3 into the inventory period. However, the fixed period still creates the possibility that catastrophe in year 19 or 20 would leave the landowner short. Additional borrowing provisions could ease this problem.

8.5.8 Carbon stored in products

Harvested material from forests and farms end up in a variety of product streams. Some are relatively short-lived such as food or pulp and paper. Others may remain 'stored' for decades or centuries such as lumber used in buildings or furniture. Schlamadinger and Marland (1999) provide some estimates and discuss issues related to carbon in the product stream. This raises the question that in harvesting a forest, should harvested product be tracked until it actually decomposes, and only then be counted as an emission of carbon requiring an allowance? In principle, the answer is 'yes' because this would provide an incentive to not finally dispose of these products if they can be salvaged or reused, and would accurately account for the time between harvest and decomposition when the carbon remained out of the atmosphere. In practice, this would require a complex tracking system both of the product and of the owners of the product to ensure that they were liable for emissions if and when they dispose of the product in such a way that the carbon was released to the atmosphere.

Simpler approaches would be to ignore this storage and assume the carbon will return to the atmosphere sooner or later. Another approach is to try to apply an average discounted tonne factor as an offset to the total harvest. Neither approach creates an incentive to prolong the life of carbon stored by not destroying structures or by recycling used lumber, assuming there is value to temporary storage. Crediting via a discounted tonne approach gets us back to the problem of estimating this discount factor, which we rejected earlier.

Bioenergy is a carbon-containing product of vegetation, and it has the potential to become more important as a 'carbon-free' energy source in a carbon-constrained world. It can be carbon-free if the biomass used is from areas where the crops are continually regrown, the carbon in the soil is not being depleted and fossil energy is not used in its production. Given the potential importance of bioenergy as a solution to climate change, getting the incentives on bioenergy right is particularly important. If one simply exempted biomass energy producers from the cap, ignoring emissions that occur in processing and combustion on the basis that these are being taken up by next year's biomass crop, it would provide no incentive to regrow the biomass.[3] Schlamadinger and Marland (1999) find that in cases of clear-cutting forest stands with large amounts of biomass the loss of carbon may never return to the predisturbance level even when accounting for energy and long-lived stocks. Similarly, disturbed cropland, as shown in Section 8.3, often has significantly less carbon than in its predisturbed state. To correctly account for such land conversion losses of carbon or non-sustainable management of land, land used to produce biomass would need to come under a cap to provide correct incentives to maintain carbon stocks in soils or in standing vegetation or detritus. Because the bioenergy would be combusted relatively quickly (weeks, months, a few years at most) after production, one could exempt emissions from combustion of the fuel (e.g. at power plant or by vehicles using a liquid fuel) completely. This approach could be applied to other product streams that are short-lived, reducing the monitoring problem to the land parcel without the need to follow the product stream.

The long-lived product streams create a more severe problem of tracking and monitoring. More investigation is needed to determine the importance of long-lived product streams. An important question is whether this carbon pool would be substantially affected by creating proper incentives to manage it. Any gain should then be balanced against the cost of establishing the necessary monitoring and tracking system for the carbon.

8.6 Conclusions

The role of sinks in climate policy has been controversial and confused. Different parties had very different motivations that led to the existing 'compromise' design of climate policy as it relates to sinks; moreover, it appears that the poor design in the Kyoto Protocol stemmed from the fact that sinks were added relatively late in the negotiation process. In addition, there was a relative vacuum of information on how big these sinks were, and how they might change over time for the parties involved. The sinks issue was relatively new and not much thought had been given on how to include them. Unfortunately, the Kyoto model for sinks, designed in a rush, has been borrowed in other proposals such as in the McCain–Lieberman Bill in the USA. The crediting approach described in these policies and proposals has led to nearly unsolvable problems. Rethinking how land use activities could be brought within climate mitigation efforts seems worthwhile.

We argue that many of the problems and concerns that analysts and policymakers have spent enormous effort trying to solve are mostly the result of the faulty architecture for sinks in the Kyoto Protocol. Like legislation to close tax loopholes that mostly creates a more complex tax code and more loopholes, attempts to patch the Kyoto approach to sinks have only led to more problems. It has set scientists and policymakers to consider imponderables such as what part of a forest is due to direct human-induced change and how much is due to nature or indirect human inducement. Hundreds of pages have been written attempting to define how many trees make a forest, and what is the difference between reforestation and afforestation.

These issues mostly disappear if one brings land use fully under a cap-and-trade system. This creates incentives both to control land use emissions and to enhance land use sinks. Whether the area is defined as a forest or not is irrelevant – all that matters is changes in the stock of carbon. The problem of leakage has been raised as a special problem related to sinks, but it can best be seen as a problem of incomplete policy, either in space or time. Bringing land use fully under the cap eliminates the problem of leakage. Instead, landowners can exercise the option to maintain or not maintain the storage, by purchasing allowances to cover emissions. This keeps the atmospheric carbon goal intact, and preserves an important flexibility in how land can be used in the future should economic condition change in different ways than we now expect. Coverage under a cap allows landowners to sell current allowances at current prices but requires them to cover future emissions with allowances when the emissions occur.

The variability in land use storage due to climate or events like forest fires is often seen as a unique problem for sinks inclusion in a carbon market. Land use carbon sinks and sources are subject to much variability but landowners regularly face much variability with regard to current uses of land. Farmers and foresters face risks of natural disasters that damage their crops or their forest stands. They make investments in the face of these uncertainties. Increasingly market intermediaries have come into being to bear or pool risk, or to allow hedging against these uncertainties. There is every reason to believe that these same types of intermediaries would come into being if there were a robust market in carbon allowances. Cost-effectiveness in carbon mitigation actions requires not only an equal carbon price across sectors but also that the risk of estimating future conditions be borne equally across sectors. Proposals that shield landowners from these risks would create an asymmetry between fossil emitters and sinks, and lead to economic inefficiency.

The literature on climate policy often portrays the management of terrestrial sinks as a very different issue than management of carbon emissions from fossil fuels, and that this difference requires special provisions in policy design. There are important biophysical aspects of sinks that make them different in some regard from fossil fuel emissions of carbon. How much sink one gets from specific management practices is highly variable across different sites, and over time. Moreover, sink storage is a combined result of direct management and earth system feedbacks. We conclude that these issues generally do not present insurmountable barriers to inclusion of terrestrial sources and sinks in a cap-and-trade system on equal terms with carbon emissions.

Rethinking the inclusion of land use activities in mitigation activities will require re-evaluating targeted levels of net emissions. The 7% below 1990 fossil emissions in the Kyoto Protocol or a return to 1990 emissions as in the McCain–Lieberman Bill that was under consideration in the US Senate has very different implications if applied to the total of fossil and land use emissions (net of sinks). The benefits of rethinking these targets, in terms of eliminating needless terminology and improving cost-effectiveness of mitigation policy, seems well worth it. There remain some ways in which land use should be treated differently, and some important issues that need further investigation. We argue that the inventory period for land use should be longer than for carbon emissions – a reporting requirement of every 10 or 20 years may be appropriate with the flexibility to produce an inventory more frequently if so desired by the landowner. Measurement, monitoring and enforcement remain important issues. Measurement need not be exact but the measurement process needs to be unbiased, and more accurate measurements will be more broadly accepted. The measurement process needs to include the ability to challenge results and processes to resolve those challenges.

There are also ancillary benefits or costs related to sinks but these also exist for mitigation of CO_2 from fossil energy emissions. These are potentially important issues that can lead to an idealized method such as a cap-and-trade system that strives for equal marginal cost abatement across sectors and countries to not be cost-effective. The first best solution in these circumstances is to fix these other problems with instruments designed specifically to address them. Adding mark-ups or mark-downs for different types of mitigation actions would require consideration of how they would likely vary by site and over time. This seems to recommend against such an approach unless a very strong case can be made. An important issue is how to deal with carbon in products harvested from vegetation. Here it is useful to distinguish between short-lived and long-lived products. Emissions with short-lived products should be exempted from a carbon charge, and instead the land from which they are produced should be under a cap so that long-term changes in carbon storage are monitored and incentives are in place to maintain or increase storage as economics dictate. Longer-lived products could require a very involved system to track their fate, as well as their owners. Whether correct incentives in this regard would substantially increase these pools compared to the case where they were simply ignored (and all carbon assumed to return to the atmosphere in relatively short order) needs further investigation.

Inclusion of land use and land-use change in climate mitigation policy has been made impossibly complex, because the architecture contained in current policies for including them is flawed. Solutions and compromises that were pragmatic or were deemed necessary to make progress on a broader agreement appear to have led us to the current climate policy architecture for land use and land-use change. Looking back now at the tangle these compromises have created makes it clear that much could be gained by reconsidering the architecture of sinks in climate policy. To do so will require some very fundamental re-evaluation of goals and targets, but the cost of not doing so means that we may leave a major source of GHGs uncontrolled, and fail to effectively use low-cost sequestration and bioenergy options that will be needed to limit atmospheric concentrations of warming substances.

Notes

[1]TEM tracks RSOLC, the amount of soil organic carbon that might decompose in the time frame of decades to centuries. Total soil organic carbon (TSOLC) would also include inert soil carbon.

[2]Depending on the merit criteria, the inclusion of sinks could lead to a different optimal level of reduction or split among countries. This example is meant to indicate that through adjusting the allowance level, any reduction amount can be achieved, including the exact level one would have achieved without sinks.

[3]Ethanol as currently produced often results in significant CO_2 emissions from fossil fuels because they are used in various parts of the processing cycle such as in distillation. If fossil fuel use is fully under a cap, including that potentially used in biomass,

this is not a problem because those emissions will be controlled under the cap covering energy use emissions. In other policies where this carbon is not priced properly, the net CO_2 emissions from ethanol production could render it worse than using petroleum products in the first place. So, this is an important concern in many policy contexts, but here we are assuming that carbon from fossil emissions are priced appropriately.

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